

## University of Dundee

### James Jurin (1684-1750)

Strasburger, Hans; Wade, Nicholas J

*Published in:*  
Journal of Vision

*DOI:*  
[10.1167/15.1.9](https://doi.org/10.1167/15.1.9)

*Publication date:*  
2015

*Document Version*  
Publisher's PDF, also known as Version of record

[Link to publication in Discovery Research Portal](#)

*Citation for published version (APA):*  
Strasburger, H., & Wade, N. J. (2015). James Jurin (1684-1750): a pioneer of crowding research? *Journal of Vision*, 15(1), 1-7. [9]. <https://doi.org/10.1167/15.1.9>

#### General rights

Copyright and moral rights for the publications made accessible in Discovery Research Portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from Discovery Research Portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain.
- You may freely distribute the URL identifying the publication in the public portal.

#### Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

# James Jurin (1684–1750): A pioneer of crowding research?

Hans Strasburger

Nicholas J. Wade

Medical Psychology & Medical Sociology,  
University of Göttingen, Göttingen, Germany  
Medical Psychology, University of München,  
München, Germany



Psychology, University of Dundee, Dundee, Scotland



**James Jurin wrote an extended essay on distinct and indistinct vision in 1738. In it, he distinguished between “perfect,” “distinct,” and “indistinct vision” as perceptual categories, and his meticulous descriptions and analyses of perceptual phenomena contained observations that are akin to crowding. Remaining with the concepts of his day, however, he failed to recognize crowding as separate from spatial resolution. We present quotations from Jurin’s essay and place them in the context of the contemporary concerns with visual resolution and crowding.**

## Introduction

“The more compounded any object is, or the more parts it consists of, it will, *ceteris paribus*, be more difficult for the eye to perceive and distinguish its several parts” (Jurin, 1738, p. 150).

Crowding is the name given to the phenomenon in which a pattern seen in isolation is more easily recognized than when in the presence of neighboring patterns. The name was coined by Holger Ehlers in 1953,<sup>1</sup> and it has become common currency in contemporary literature (Song, Levi, & Pelli, 2014; Strasburger, 2014; see Levi, 2008, and Strasburger, Rentschler, & Jüttner, 2011, for reviews). Crowding was long conflated with the reduction of resolution in peripheral vision. The crowding phenomenon itself has a longer pedigree, and we wish to draw attention to what could be an 18th-century description of it by James Jurin (Figure 1).

Jurin was an ardent Newtonian and gained his knowledge of optics from personal acquaintance with Newton (Wade, 2004). Jurin served as secretary of the Royal Society of London from 1721–1727 and was president of the Royal College of Physicians of London

in the year of his death. He wrote on medical matters as well as those of natural philosophy. As secretary of the Royal Society, he would have been familiar with the advances in science discussed and demonstrated at its meetings. His work on what he termed “distinct vision” was probably stimulated by Robert Hooke’s demonstration of the limits of vision, indicating that a separation of less than 1 min visual angle could not be discriminated (see Wade, 2004). Hooke’s considerations of the limits of visual resolution were discussed at length in Smith’s *A Compleat System of Opticks in Four Books* (1738) to which Jurin’s essay was appended. At about the same time, Porterfield (1737) had written the first of two essays on eye movements. Porterfield was well aware that visual resolution declined in the peripheral retina and addressed the issue of our general unawareness of this. He attributed the latter to rapid eye movements over a scene so that different parts of it could be seen distinctly.

A variety of terms was used to distinguish between the high resolution around the point of fixation and its reduction with eccentricity. These were principally “distinct and indistinct vision,” “direct and indirect vision,” and, more recently, “central and peripheral vision” (see appendix in Strasburger, 2014). However, whereas the last two pairs of terms refer to a locus on the retina, Jurin’s distinction of “distinct” versus “perfect” vision refers to a perceptual category and is, as such, open to interpretation. Its ready association with explanatory concepts has hindered its understanding for a long time. That it refers to a perceptual rather than a physical or physiological category, namely that the clarity of the percept is separate from the absence of optical blur, is revealed by the experimental paradigm by which distinct vision is defined:

“9. Distinct vision may therefore not unfitly be divided into the two following sorts, or species,

Citation: Strasburger, H., & Wade, N. J. (2015). James Jurin (1684–1750): A pioneer of crowding research? *Journal of Vision*, 15(1):9, 1–7, <http://www.journalofvision.org/content/15/1/9>, doi:10.1167/15.1.9.



Figure 1. A portrait of James Jurin (1684–1750) combined with a clock face of the type he described together with the title page of his essay, which was appended to Smith's (1738) *Opticks*.

AN  
ESSAY  
UPON  
DISTINCT AND INDISTINCT  
VISION.

TO DR. SMITH.

SIR,

As my first entrance upon the following speculation was principally owing to the hints and observations contained in your Book, the greatest part of which I have had by me in print for several years, and I was encouraged to pursue it thus far by the admirable facility of those methods of computation which you have therein delivered, I look upon whatever may be of any value in these papers, as more yours than mine. To you therefore I send them, to make what use of them you think proper.

I might have added a great many other uncommon and hitherto unobserved appearances, particularly in looking thro' small perforations in cards or thin plates, but that I found it would take up too much time to digest them into order and insert them in their proper places; and to retard the publication of your long expected work for any thing of mine, would be doing a sensible injury to the publick. I am,

SIR,

your most affectionate friend,  
and very humble servant,

JAMES JURIN.

Objects when seen distinctly. 1. AN object is said to be seen distinctly, when its outlines appear clearly, when its outlines appear clear and well defined, and the several parts of it, if not too small, are plainly distinguishable, so as that we can easily compare them one with another, in respect to their figure, size and colour. For instance, the words of this book are distinctly seen, when the letters appear well defined, and their shape and the intervals between them are plainly perceived and

P 2

namely, Vision perfectly distinct, or *Perfect Vision*, and Vision imperfectly distinct, which I shall usually call, simply, by the name of *Distinct Vision*.

“10. Vision perfectly distinct, or *Perfect Vision*, is that, in which the rays of a single pencil are collected into a single physical, or sensible [i.e. sensitive] point on the *Retina*.

“11. Vision imperfectly distinct, or simply *Distinct Vision*, is that, in which the rays of each pencil are not collected into a sensible point, but occupy some larger space upon the *Retina*, yet so as that the object is distinctly perceived.” (Jurin, 1738, p. 116)

The paradigm by which blur was induced was by bringing the print closer to the eye than accommodation would allow.<sup>2</sup> Distinct vision is then that case in which the percept is clear even though the retinal image is blurred. With blur constant, larger print will appear distinct as Jurin explains elsewhere in his essay. The more compounded any object is, the less distinct the percept, as Jurin indicated in the opening quotation. In indirect vision, one might add, optical blur and spatial resolution are not the limiting factors for large print, and, with sufficient letter spacing, the percept would be

called distinct in Jurin's terminology. So is Jurin's *indistinct vision* crowding?

## Early accounts of visual resolution

Classical considerations of visual acuity were in terms of distance or distant objects. Distinguishing double stars provided one of the earliest forms of assessing the precision of vision, and it was so applied in Egypt over 5,000 years ago (Hirschberg, 1982; Bohigian, 2008). An alternative technique, introduced in the 17th century, involved presenting small objects of regular size and determining the distance at which they could no longer be discerned. For example, Daça de Valdes (1623) measured the distance at which a row of mustard seeds could not be counted; he also measured the distance at which small print could be read. These techniques were used to prescribe the strength of eyeglasses. Hooke (1674) determined the limits of visual resolution to be around 1 min for most individuals, but variations, depending upon stimulus and the conditions of stimulation, were also established by later researchers. Differences between using one or two lines were noted as was the effect of stimulus intensity. A great deal was learned about visual resolution by this simple procedure of varying the distance of observation (see Wade, 2007, for review).

Jurin amplified a point made by Hooke, namely that the response to any stimulation is dependent upon intensity as well as spatial extent: “A star, which appears only as a lucid point thro’ a telescope, not subtending so much as an angle of one second, is visible to the eye, though a white or black spot of 25 or 30 seconds is not to be perceived” (Jurin, 1738, p. 148). He employed a range of visual patterns, which included white discs on black backgrounds and vice versa as well as thin black lines on a white ground and vice versa. Jurin found that a line could be perceived at a greater distance than a spot of similar width and that long lines were visible at greater distances than short lines of the same width. He also found that detecting a gap between two black lines provided different estimates of visual resolution than detecting the presence of a single black line.

## Seeing compounded objects

It is in this last context that Jurin described two examples of what is now called crowding. One concerned the observation of an arrangement of numbers, and the other involved an object in the environment (a clock face). The first was prefaced by the statement given at the head of this article:

“173. [...] For instance, it is somewhat difficult for the eye to judge how many figures are contained in the following numbers, 1111111111; 1000000000. But if we divide the figures in this manner, 1111,1111; 10000,0000; so as to constitute several objects less compounded, we can more easily estimate the number of figures contained in each of those numbers; and more easily still, if we thus divide them, 1,111,111,111; 1,000,000,000.” (Jurin, 1738, p. 150)

A rough calculation shows that in normal reading these patterns are quite large horizontally—around  $4.5^\circ$  at 30 cm distance and having  $0.5^\circ$  center-to-center letter distance—and are thus expected to undergo crowding<sup>3</sup> (Toet & Levi, 1992). A simpler and perhaps more direct way to assess whether crowding will occur in the above examples is by Pelli’s concept of the uncrowded window, which, for a normal observer, is about nine characters wide (Pelli & Tillman, 2008; more direct because critical distance in crowding is largely independent of letter size—Strasburger, Rentschler, & Harvey, 1991; Pelli, Palomares, & Majaj, 2004—but scales with eccentricity and is thus somewhat independent of viewing distance). So the above 10-character examples in the quotation are all expected to undergo crowding.<sup>4</sup>

Jurin provided another example in which—as in crowding—the elements of compound objects or patterns were more difficult to see than single elements:

“175. [...] For instance, the hour I. upon a dial plate may be seen at such a distance, as the hours II, III, IIII, are not to be distinguished at, especially if the observer be in motion, as in a coach, or on horseback, or even in a boat upon water. This may easily be experienced in looking at a dial where the interval between the black or gilt strokes are equal to the breadth of those strokes; and much more easily where the intervals are of less breadth, which is a defect in large dials that are to be seen at a great distance. For in these, the intervals ought to be considerably broader than the strokes.” (Jurin, 1738, p. 151)

At the acuity limit that is considered here, i.e., at approximately 1 min of arc stroke separation in Roman number “II,” the edge-to-edge separation in all the compound number patterns is below the limit of 3–5 min of arc reported by Siderov, Waugh, and Bedell (2013a) to be the critical, constant range for foveal crowding (cf. also Coates & Levi, 2013, and Siderov, Waugh, & Bedell’s reply, 2013b). However, with unsteady fixation as implied in the example, it seems likely that the patterns are seen slightly off center, which will increase crowding dramatically. This brings us to our next topic.

## Central and peripheral vision

Crowding is weak in the very center of the fovea (see above) but quickly increases outside such that it is the overriding limit to recognition of compound patterns at a few degrees eccentricity and all of peripheral vision. Jurin said little about the latter, but many others had done before him (see Wade, 1998). Ptolemy in the second century and Ibn al-Haytham (also known by his Latinized name of Alhazen) in the 11th discussed distinct and peripheral vision together, and the latter extended his experiments using written words as stimuli to peripheral extents, which resulted in the letters being illegible:

“The experimenter should then gently move the strip [with a word written on it] along the transverse line in the board, making sure that its orientation remains the same, and, as he does this, direct his gaze at the middle strip while closely contemplating the two strips. He will find that as the moving strip gets farther from the middle, the word that is on it becomes less and less clear ... as the moving strip gets farther from the middle, the



word that is on it decreases in clarity until he ceases to comprehend or ascertain its form. Then if he moves it further, he will find that the form of that word becomes more confused and obscure.” (Ibn al-Haytham, translated in Sabra, 1989, pp. 244–245)

The magnitudes of these extents were not given, and many centuries were to pass before values were derived. Nonetheless, the reduction in clarity with retinal eccentricity was well known. Ptolemy considered that “what is seen by the central rays on the visual axis is seen more clearly than objects at the side” (Lejeune, 1956, p. 20). Note that in Ibn al-Haytham’s experiment cited above—because he used words rather than isolated letters or dots as stimuli—clarity will have been limited by crowding, not by acuity (Pelli et al., 2007). However, because there was no comparison to clarity of single letters, crowding was missed. Purkinje (1825) employed his perimeter to determine the dimensions of the visual fields, but he did not assess peripheral acuity. The quantitative reduction in resolution was measured only much later by Aubert and Foerster (1857) who showed that (photopic) two-point resolution follows a linear function with eccentricity (and that visual-field limits for scotopic letter recognition are horizontal ellipses). From experiments with an extracted rabbit eye, Aubert and Foerster were further aware that the reduction of resolution was not caused by optical blur (1857, p. 35), and they suggested it depends on cone density.

## Why were Jurin’s observations overlooked?

Jurin confined his observations to central vision, and he interpreted “crowding” in terms of small eye movements: “From the same cause of the instability of the eye it must be, *ceteris paribus*, more difficult to perceive and distinguish the parts of any compound object, when each of those parts subtends a very small angle, than to see a single object of the same magnitude as one of those parts” (1738, p. 151). It was not possible to measure such small eye movements at that time, but the concern with their effects, together with the pervading reductionist approach of the time, could have been a reason for the neglect of Jurin’s observations. When eye movements were eventually measured, interest centered on the targets that were briefly fixated (Wade, Tatler, & Heller, 2003).<sup>5</sup> Because it was well known that resolution was superior on the visual axis, attention was confined to this.

Thus, our visual experience does not correspond to measures of peripheral acuity. It was precisely this

appreciation that led Porterfield to initiate interest in eye movements:

“Now, though it is certain that only a very small Part of any Object can at once be clearly and distinctly seen, namely, that whose Image on the *Retina* is in the *Axis* of the Eye; and that the other Parts of the Object, which have their Images painted at some Distance from this same *Axis*, are but faintly and obscurely perceived, and yet we are seldom sensible of this Defect; and, in viewing any large Body, we are ready to imagine that we see at the same Time all its Parts equally distinct and clear: But this is a vulgar Error, and we are led into it from the quick and almost continual Motion of the Eye, whereby it is successively directed towards all the Parts of the Object in an Instant of Time.” (1737, pp. 185–186).

What is of interest in this quotation (and numerous similar ones that followed by other authors) is that considerations of visual resolution took precedence over direct visual experience. Another example from later in the same century is “Few things, at first, appear more incredible to a person, not conversant in optics, than that he does not, at any one time, see distinctly a surface larger than the head of a pin” (Wells, 1792, p. 106). Such views concentrated attention on central vision and eventually on eye movements.

Despite the fact that both Jurin (1738) and Mayer (1755) demonstrated differences in visual resolution between simple and compound stimuli, the demands of experimental elegance favored the use of single simple stimuli. The use of dots, lines, gratings, and grids was not seriously pursued by clinicians, partly because of the inconvenience of varying the distance of observation for fixed stimuli. They adopted the alternative approach of viewing stimuli of variable size at a fixed or short range of distances. In the 19th century, letter shapes and sizes were examined more systematically because typefaces could be varied in size with ease and could be readily reproduced (Wade, 2008). Letter shapes were produced by K  chler (1853) and were extended with great precision and standardized by Jaeger (1854). His test types were based on the assumption that central acuity was essential for reading and that an adequate test would involve letter sequences; Jaeger also developed a test with vertical lines of decreasing width. An alternative approach was pursued by Snellen (1862): He devised geometrical shapes of differing size and orientation and also letters of particular configurations. Under the guidance of Donders at Utrecht, a functional test of acuity was developed. Donders (1864) introduced the term “visual acuity” for what had previously been described as the “minimum visible or separable,” and he was quick to apply the new method for assessing acuity in his own

studies of declining visual resolution with age. In addition to using a variety of letters, Snellen (1882) used a single, well-defined “E” in different sizes and orientations so that any patient could perform the task. Snellen’s isolated shapes were called optotypes, and a modification of them, avoiding rectangular elements, was introduced by Landolt in 1888. The Landolt C or ring consisted of a circle with a gap in it; the size of the ring and the orientation of the gap could be varied, and the observer’s task was to detect the orientation of the gap in the ring. This concentration on single stimuli reduced the probability of detecting crowding in central or peripheral vision.

Parallel to the advances in the study of central acuity, quantitative mappings of peripheral vision were made. Aubert and Foerster (1857) in Breslau studied spatial resolution on the retina, following the methods adopted by Weber (1851) in his studies of spatial resolution on the skin. They found that two-point resolution for black dots on a white background followed a linear function up to the blind spot in photopic vision (i.e., that resolution follows an inverse-linear function). The perimeter depicted in that paper was refined and presented at the Ophthalmology Congress in Paris held in 1867, and it became widely known as the “Försterische Perimeter.” Wertheim (1894) in Berlin presented detailed measurements of grating resolution in the visual field. Again, however, with respect to the spatial sense of the retina, the preoccupation with reductionist questions of spatial resolution remained, and stimuli were simple and presented singly, i.e., they were unsuitable for uncovering crowding. Things changed only in the first half of the 20th century with Korte (1923), Ehlers (1936, 1953), Woodworth (1938), and Stuart and Burian (1962).

A final factor concerns the difficulty of determining crowding in peripheral vision during observations in the natural environment. Whenever a pattern in peripheral vision is crowded (which is the rule rather than the exception), the comparison with the same pattern in isolation is not available, and a quick, unconscious eye movement will solve the puzzle for the observer. This could account for Jurin’s restriction of its description to central vision.

## Conclusion

Jurin’s concept of *indistinct vision* refers to a degraded clarity of the *percept* that is not rooted in a degraded retinal image and which depends on the visual object’s compoundedness. From today’s knowledge, these are characteristics of crowding. Indirect vision, i.e., vision off center—where crowding rather than resolution is the overriding limit to pattern recognition—is not mentioned in Jurin’s meticulous analysis. But in the main

examples given, it is apparent that crowding has played an important or perhaps the overriding role. Remaining with the concepts of his contemporaries, however, Jurin failed to recognize crowding as separate from spatial resolution, and the crowding phenomenon was overlooked for another two centuries.

*Keywords:* crowding, history, peripheral vision, fovea, acuity, pattern recognition, spatial vision

## Acknowledgments

We thank an anonymous reviewer for critical comments. The University of Göttingen provided Open Access funds.

Commercial relationships: none.

Corresponding author: Hans Strasburger.

Email: strasburger@uni-muenchen.de.

Url: www.hans.strasburger.de.

## Footnotes

<sup>1</sup> H. Ehlers (1936, pp. 61–62) earlier described the phenomenon in a way similar to present-day accounts and spoke of characters in *close type*, with which recognition is limited by our *psychic capacity* (we would say *cortical* today), as opposed to *less close together* or *interspaced* characters with recognition limited by our *visual capacity*. He then noted that the number of recognized characters scales with eccentricity. After his talk, a discussant belittled Ehlers’ findings with reference to Weymouth, Hines, Acres, Raaf, & Wheeler’s (1928) reports on peripherally reduced acuity. Woodworth (1938) described the phenomenon with the concept of a “span of apprehension”: “It seems strange that a word should need to be brought closer [to the fixation point] than a single letter. If the single letters can be read, why not the word composed of these letters? The answer is a mutual interference or masking of the letters in indirect vision” (p. 720). Again, that went unnoticed (as noted by Pelli et al., 2007). The importance of the matter was recognized only much later by Stuart and Burian (1962). Korte (1923) described related phenomena in great detail (cf. Strasburger, 2014).

<sup>2</sup> The procedure will work with most adults as accommodative power is rapidly lost in the first four decades of life. Elsewhere in the text, Jurin stated that blur can also be achieved by having the stimulus farther away than the far point (which will only hold for myopic observers) and tried to determine the latter by optical and perceptual arguments (1738, pp. 134–136).

<sup>3</sup> From an online version of Smith's book and at an assumed capital-letter height in it of 2.5 mm, the width of the example would be ~24 mm or around 4.5° at 30 cm reading distance. If the letter string's center is fixated, then, from Toet and Levi's (1992) figure 4, for that fixation, the critical (75% correct) center-to-center letter distance at 2.2° eccentricity (half the example's width) can be read off as being just under 0.5°. Obviously, the digits could be fixated one-by-one and would then each be seen clearly, but the overall pattern would still be crowded.

<sup>4</sup> Shaw (1969) has studied the role of spaces in 10-letter strings of 4° horizontal subtense (cf. the review in Strasburger et al., 1991).

<sup>5</sup> Aubert and Foerster (1857, p. 3), for example, used an electrical spark (from a "Riesssche Flasche") for brief presentation but also had observers simply fixate on a marker (1857, p. 15).

## References

- Aubert, H. R., & Foerster, C. F. R. (1857). Beiträge zur Kenntniss des indirecten Sehens (I). Untersuchungen über den Raumsinn der Retina [Translation: Contributions to the knowledge on indirect vision (I). Studies on the spatial sense of the retina]. *Archiv für Ophthalmologie*, 3, 1–37.
- Bohigian, G. M. (2008). An ancient eye test – using the stars. *Survey of Ophthalmology*, 53, 536–539. [PubMed]
- Coates, D. R., & Levi, D. M. (2013). Contour interaction in foveal vision: A response to Siderov, Waugh, and Bedell (2013). *Vision Research*, 96, 140–144. [PubMed]
- Daça de Valdes, B. (1623). *Uso de los antoios* [Translation: *The use of eyeglasses*]. Seville: Perez.
- Donders, F. C. (1864). *On the anomalies of accommodation and refraction of the eye*. (W. D. Moore, Trans.). London: New Sydenham Society.
- Ehlers, H. (1936). The movements of the eyes during reading. *Acta Ophthalmologica*, 14, 56–63. [Abstract]
- Ehlers, H. E. (1953). Clinical testing of visual acuity. *AMA Archives of Ophthalmology*, 49, 431–434. [Abstract]
- Hirschberg, J. (1982). *The history of ophthalmology. Vol 1. Antiquity*. (F. C. Blodi, Trans.). Bonn, Germany: Wayenborgh.
- Hooke, R. (1674). *Animadversions on the first part of the machina coelestis of the honourable, learned, and deservedly famous astronomer Johannes Hevelius, consul of Dantzick, together with an explication of some instruments*. London: Martyn.
- Jaeger, E. (1854). *Ueber staar und staaroperationen* [Translation: *Concerning cataracts and cataract operations*]. Vienna: Seidel.
- Jurin, J. (1738). An essay on distinct and indistinct vision. In R. Smith (Ed.), *A compleat system of opticks in four books, viz. a popular, a mathematical, a mechanical, and a philosophical treatise* (pp. 115–171). Cambridge, UK: Author.
- Korte, W. (1923). Über die Gestaltauffassung im indirekten Sehen [On the apprehension of Gestalt in indirect vision]. *Zeitschrift für Psychologie*, 93, 17–82.
- Küchler, H. (1853). *Schriftnummerproben für Gesichtslleidende* [Translation: *Text and number tests for the poor sighted*]. Darmstadt, Germany: Diehl.
- Landolt, E. (1888). Méthode optométrique simple [Translation: A simple optometric method]. *Bulletins et Memoires de la Société Française d'Ophtalmologie*, 6, 213–214.
- Lejeune, A. (Ed. and Trans.). (1956). *L'Optique de Claude Ptolémée dans la version Latine d'après l'Arabe de l'Émir Eugène de Sicile* [Translation: *The Optics of Claudius Ptolemy in the Latin version after the Arab Eugene Emir of Sicily*]. Louvain: Université de Louvain.
- Levi, D. M. (2008). Crowding – An essential bottleneck for object recognition: A minireview. *Vision Research*, 48(5), 635–654. [PubMed]
- Mayer, T. (1755). Experimenta circa visus aciem [Translation: Experiments on visual acuity]. *Commentarii Societatis Regiae Scientiarum Gottingensis*, 4, 97–112.
- Pelli, D. G., Palomares, M., & Majaj, N. J. (2004). Crowding is unlike ordinary masking: Distinguishing feature integration from detection. *Journal of Vision*, 4(12):12, 1136–1169, <http://www.journalofvision.org/content/4/12/12>, doi:10.1167/4.12.12. [PubMed] [Article]
- Pelli, D. G., & Tillman, K. A. (2008). The uncrowded window of object recognition. *Nature Neuroscience*, 11, 1129–1135. [PubMed]
- Pelli, D. G., Tillman, K. A., Freeman, J., Su, M., Berger, T. D., & Majaj, N. J. (2007). Crowding and eccentricity determine reading rate. *Journal of Vision*, 7(2):20, 1–36, <http://www.journalofvision.org/content/7/2/20>, doi:10.1167/7.2.20. [PubMed] [Article]
- Porterfield, W. (1737). An essay concerning the motions of our eyes. Part 1. Of their external



- motions. *Edinburgh Medical Essays and Observations*, 3, 160–263.
- Purkinje, J. (1825). *Beobachtungen und Versuche zur Physiologie der Sinne. Neue Beiträge zur Kenntniss des Sehens in subjectiver Hinsicht* [Translation: *Observations and experiments on the physiology of the senses. New contributions to the knowledge of vision in its subjective aspect*]. Berlin, Germany: Reimer.
- Sabra, A. I. (Trans. and Ed.). (1989). *The optics of Ibn Al-Haytham. Books I–III. On direct vision*. London: The Warburg Institute.
- Shaw, P. (1969). Processing of tachistoscopic displays with controlled order of characters and spaces. *Perception & Psychophysics*, 6, 257–266. [Article]
- Siderov, J., Waugh, S. J., & Bedell, H. E. (2013a). Foveal contour interaction for low contrast acuity targets. *Vision Research*, 77, 10–13. [PubMed]
- Siderov, J., Waugh, S. J., & Bedell, H. E. (2013b). Foveal contour interaction on the edge: Response to ‘Letter-to-the-Editor’ by Drs. Coates and Levi. *Vision Research*, 96, 145–148. [PubMed]
- Smith, R. (1738). *A compleat system of opticks in four books, viz. a popular, a mathematical, a mechanical, and a philosophical treatise*. Cambridge, UK: Author.
- Snellen, H. (1862). *Letterproeven tot bepaling der gezichtsscherpte* [Translation: *Letter tests to determine visual acuity*]. Utrecht, Netherlands: Van de Weyer.
- Snellen, H. (1882). *Optotypen, tot bepaling der gezichtsscherpte, 2nd ed.* [Translation: *Optotypes, to determine visual acuity*]. Utrecht, Netherlands: Van de Weyer.
- Song, S., Levi, D. M., & Pelli, D. G. (2014). A double dissociation of the acuity and crowding limits to letter identification, and the promise of improved visual screening. *Journal of Vision*, 14(5):3, 1–37, <http://www.journalofvision.org/content/14/5/3>, doi:10.1167/14.5.3. [PubMed] [Article]
- Strasburger, H. (2014). Dancing letters and ticks that buzz around aimlessly – On the origin of crowding. *Perception*, 43, 963–976. [PubMed] [Article]
- Strasburger, H., Rentschler, I., & Harvey, L. O., Jr. (1991). Contrast thresholds for identification of numeric characters in direct and eccentric view. *Perception & Psychophysics*, 49, 495–508. [PubMed] [Article]
- Strasburger, H., Rentschler, I., & Jüttner, M. (2011). Peripheral vision and pattern recognition: A review. *Journal of Vision*, 11(5):13, 1–82, <http://www.journalofvision.org/content/11/5/13>, doi:10.1167/11.5.13. [PubMed] [Article]
- Stuart, J. A., & Burian, H. M. (1962). A study of separation difficulty: Its relationship to visual acuity in normal and amblyopic eyes. *American Journal of Ophthalmology*, 53, 471–477. [PubMed]
- Toet, A., & Levi, D. M. (1992). The two-dimensional shape of spatial interaction zones in the parafovea. *Vision Research*, 32(1), 1349–1357. [PubMed]
- Wade, N. J. (1998). *A natural history of vision*. Cambridge, MA: MIT Press.
- Wade, N. J. (2004). Visual neuroscience before the neuron. *Perception*, 33, 869–889. [PubMed] [Article]
- Wade, N. J. (2007). Image, eye and retina (invited review). *Journal of the Optical Society of America A*, 24, 1229–1249. [PubMed] [Article]
- Wade, N. J. (2008). Snellen’s letters. *Perception*, 37, 167–170. [PubMed] [Article]
- Wade, N. J., Tatler, B. W., & Heller, D. (2003). Dodging the issue: Dodge, Javal, Hering, and the measurement of saccades in eye movement research. *Perception*, 32, 793–804. [PubMed] [Article]
- Weber, E. H. (1998). *Die Lehre vom Tastsinne und Gemeingefühle, auf Versuche gegründet* [Translation: *On the sense of touch and coenaesthesia, based on experiments*]. Vieweg, Braunschweig. [E-Book] Available at <http://books.google.de/books?id=9HxQAAAACAAJ>.
- Wells, W. C. (1792). *An essay upon single vision with two eyes: Together with experiments and observations on several other subjects in optics*. London: Cadell.
- Wertheim, T. (1894). Über die indirekte Sehschärfe. *Zeitschrift für Psychologie & Physiologie der Sinnesorgane*, 7, 172–187.
- Weymouth, F. W., Hines, D. C., Acres, L. H., Raaf, J. E., & Wheeler, M. C. (1928). Visual acuity within the area centralis and the relation to eye movements and fixation. *American Journal of Ophthalmology*, 11, 947–960.
- Woodworth, R. S. (1938). *Experimental psychology*. New York: Holt.